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Model Study of Air Coupled Surface Waves

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Model Study of Air Coupled Surface Waves

by

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ABSTRACT

Flexural waves generated in a thin plate by a spark source are used to investigate properties of air-coupled surface waves. Both ground shots and air shots are simulated in the model. Effects of source elevation, fetch of air pulse, cancellation by destructive interference are studied.

INTRODUCTION

It has been shown in earlier experimental and theoretical investigations (Press and Ewing, 1951a, 1951b, Press, Crary, Oliver and Katz, 1951) that despite the large density contrast between the two media, coupling of compressional waves in air to surface waves in solids is appreciable when the phase velocity of the surface wave equals the speed of sound in air. The basic mechanism of coupling may be understood from Lamb's treatment (1932, pp. 413-415) of the effect of a travelling disturbance. Consider a pressure pulse generated by a spark or explosion in air in the vicinity of the surface of a layered, solid elastic medium. To a first approximation we may neglect the reaction of the surface waves and treat the air pulse as a disturbance travelling with the speed of sound in air over the surface of a dispersive medium. Lamb showed that only those surface waves are excited whose phase velocity equals that of the travelling disturbance, in this case the air pulse. For dispersive surface waves a discrete frequency is usually associated with a given phase velocity. Air-excited (or air-coupled) surface waves occur therefore as a train of constant frequency oscillations having a phase velocity equal to the speed of sound in air. Since the propagation velocity of a train of waves of a given frequency is the group velocity it is apparent that the wave system generated by a travelling disturbance either precedes or follows the disturbance

according as the group velocity is greater than or less than the phase velocity.

In this paper we describe the results of a seismic model study of air-coupled flexural waves. The model offers greater flexibility in varying such parameters as source height, source directionality, propagation distance or fetch of the air pulse, than was possible in earlier field experiments with explosive sources. Although these experiments deal with flexural waves, the results are of a general nature and may be applied to other types of air-coupled surface waves.

EXPERIMENTAL PROCEDURE

The pressure pulse was generated with a spark obtained by first charging a 1 mfd. condenser to 1500 volts and then discharging it across a 1/8 inch air gap. Using a motor-driven commutator switch, a pulse repetition rate of 10 sparks per second could be realized. Flexural waves generated by the pressure pulse in a plate of 24st aluminum, 1/32 inch thick and 4 ft. by 6 ft. in lateral dimensions, were detected by a small barium titanate transducer 1/25 inch thick and 3/32 inch in diameter. After suitable amplification the waves were displayed on a cathode ray oscilloscope whose sweep was triggered by the spark discharge. The resultant stationary pattern on the oscilloscope could be photographed utilizing the usual technique of multiple exposures to produce a seismogram of a spread of detectors. Additional details of model apparatus and methods may be found in a previous paper (Oliver, Press and Ewing, 1954).

EXPERIMENTAL RESULTS

Two types of sources may be distinguished, a ground shot in which elastic energy enters the dispersive medium primarily in the vicinity of the source and an air shot in which the outward propagating air disturbance continues to impulse the ground for some distance beyond the source. A combined ground and air shot is possible as would

be the case for an explosion at the surface of the dispersive medium.

Ground Shot.

To simulate a ground shot the spark was located 3/8 of an inch above the aluminum plate and the outward propagating air wave was blocked by a plate of absorbent sponge rubber. The experimental set-up is depicted at the bottom of Figure 1 where S is the source, B the air barrier, D the detector and d the shot detector distance.

Flexural waves from the ground shot model detected at 1/2 inch intervals in the range 8.4-11.9 inches from the source are shown in Figure 1. The characteristic dispersion of these waves evident in the seismogram has been treated by numerous investigators and only a brief discussion need be given here. It is well known that flexural waves are governed by the equation

$$\frac{\tanh \frac{kH}{2}\eta_2}{\tanh \frac{kH}{2}\eta_1} = \frac{(1+\eta_2^2)^2}{4\eta_1\eta_2} \tag{1}$$

where $\eta_2 = (1 - c^2/\beta^2)^{1/2}$, $\eta_1 = (1 - c^2/\alpha^2)^{1/2}$, $k = 2\pi/Tc$,

α, β are the compressional and shear velocities respectively, c is the phase velocity, T the period and H the plate thickness. For wave lengths long compared to the plate thickness (1) reduces to

$$\frac{c^2}{\beta^2} = \frac{1}{3}(kH)^2(1 - \beta^2/\alpha^2) \tag{2}$$

When elastic constants appropriate to 24 st aluminum (α =20,300 ft/sec, β =10,400 ft/sec) are inserted in (1) the theoretical phase velocity curve shown in Figure 2 can be computed. Also plotted in the figure is the theoretical group velocity curve obtained from the familar equation $U = c + kH\, dc/dkH$ by numerical differentiation. Experimental values of phase and group velocity may be obtained as a function of period from the seismogram in Figure 1. It is seen that the experimental points agree fairly well with the appropriate theoretical curves of Figure 2.

Air Shot.

To simulate a source in which energy is transmitted to the dispersive medium primarily by a horizontally travelling air pulse the experimental procedure depicted at the bottom of Figure 3 was utilized. In this case the barrier was placed between the spark and the plate to minimize the effect of the shock wave arriving from a direction normal to the plate. Recordings from a spread of detectors placed at 1/2 inch intervals in the range 8.4-11.9 inches from the source are shown in Figure 3. In marked contrast to the seismogram for the ground shot, dispersion is minimized, the principal signal consisting of a train of constant period waves having a phase velocity of 1100 ft/sec equal to the speed of sound in air. From the theoretical phase velocity curve

in Figure 2 we find that c=1100 ft/sec corresponds to a period of 49 μs This is in excellent agreement with the value of 48 μs obtained from the constant period train of waves in Figure 3. From the discussion in the introduction it is clear that these are air-coupled flexural waves which have been excited by the air shot.

Air-Ground Shot.

A combined air-ground shot is obtained simply by removing all barriers, as is indicated at the bottom of Figure 4. The resultant seismogram in Figure 4 shows both the dispersive train of the ground shot and the constant frequency train of the air shot. Upon more detailed examination of the seismogram it is found that the dispersive train contains only those waves whose phase velocity exceeds or equals the speed of sound in air. The longer period oscillations having phase velocities smaller than the speed of sound in air have been replaced by constant period air-coupled waves.. This is shown clearly in Figure 5 where ground, air-ground and air shots for a shot detector distance of 10.4 inches are displayed in succession. It is evident that the ground and air-ground shot traces match perfectly up to the point on the former trace where waves with period longer than the air-coupled wave period arrive. In contrast the air-ground and air shot traces match only for the air-coupled waves, being dissimilar in amplitude and phase for

waves whose phase velocity exceeds the speed of sound in air.

Effect of fetch of air wave.

By varying the position of the barrier as shown at the bottom of Figure 6 the effect of changes in fetch of the air wave can be studied.

The wave lengths of air-coupled waves in this experiment are about .7 inches. At the first position of the barrier, 1 1/4 inches or roughly 2 wave lengths from the source, air-coupled waves are completely lacking and the dispersive flexural waves from a ground shot occupy the entire seismogram. Beginning at 3 inches or 4 wave lengths, changes begin to occur. With increasing fetch beyond this point long period flexural waves travelling with phase velocities less than the speed in air diminish in amplitude, and are replaced cycle by cycle with air coupled oscillations. It is seen on the seismogram that the development of the air-coupled train continues to the last trace where the barrier is only 2 wave lengths from the detector. We conclude that maximum fetch is necessary to fully excite a train of air-coupled waves and that propagation of the air pulse to distances of several wave lengths from the source is sufficient to begin alteration of the seismogram from ground shot to air-ground shot character.

Effect of variation of height of air shot.

In field experiments it is difficult to study this effect, especially when the source height is of the same order as the shot-detector

distance. The model set-up is depicted at the bottom of Figure 7. In this case the shot-detector distance was fixed at 11.9 inches and the source height was varied in 1/2 inch intervals to a height of 4 inches.

In earlier work on air-coupled Rayleigh waves (Press and Ewing, 1951b) it was shown both theoretically and experimentally that air-coupled waves are independent of source height providing it was small compared to the shot-detector distance. From the model seismogram in Figure 7 we may see how these results are modified for higher source elevations. Air-coupled waves, as identified by their period and lack of dispersion, are independent in amplitude and phase of source elevation. (Vertical markers identify these waves on the seismogram of Figure 7.) However the absolute time of beginning of air-coupled waves is seen to increase with source elevation. Shorter period, gradually dispersive waves with duration increasing as source elevation arrive prior to the air-coupled waves. These change rapidly in character with increasing source elevation.

Again resorting to Lamb's theory of travelling disturbances we may qualitatively explain these results. The pressure pulse leaving an elevated air source strikes the plate at varying angles of incidence. The apparent or phase velocity of the pulse along the plate varies from infinite value directly beneath the source to the speed of sound in air

at large horizontal distances from the source. At any point in the plate those flexural waves are excited whose phase velocity matches the apparent velocity of the air pulse. Thus near the source where the apparent velocity of the pressure pulse is high and varies rapidly, shorter period, faster travelling, dispersive flexural waves are initiated. At large distances from the source the apparent velocity varies more slowly, approaching asymptotically the speed of sound in air. Here constant period air-coupled waves are initiated, dispersion effects being negligible. Since group velocity exceeds phase velocity for flexural waves, the short period dispersive waves excited near the source will be the first to arrive at a distant point. With increasing source elevation the horizontal distance increases to the point on the plate where the apparent velocity of the air pulse approximates the speed of sound in air. It follows that the arrival time of the constant period train increases with elevation. For quantitative explanation of the effect of source elevation, appropriate modification of the wave theory given in earlier papers (Press and Ewing, 1951a, 1951b) must be made.

Destructive interference.

It has been pointed out that air shots spaced in the shot-detector line at intervals of one-half wave length for air-coupled waves can result in cancellation of these oscillations (Press, 1953). This phenomenon may be readily demonstrated by placing a reflecting wall a distance

of 1/4 or 3/4 wave length behind the shot, as in the lower trace of Figure 8. The upper trace represents an air-ground shot. Cancellation of the air-coupled wave is readily observable for the former case. In view of the constant period characteristic of air-coupled surface waves we conclude that they may readily be cancelled by this technique.

ACKNOWLEDGMENTS

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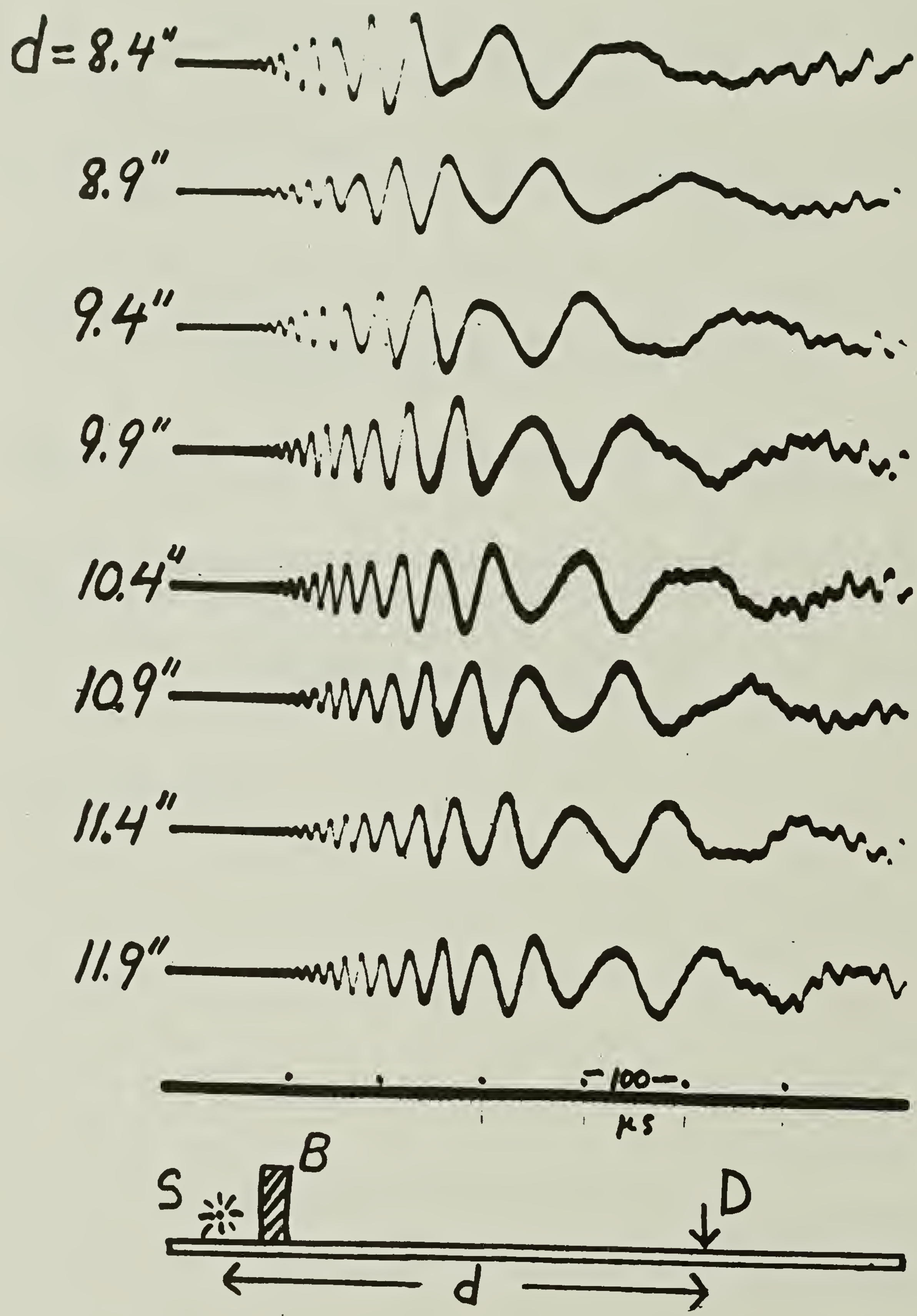

Fig. 1. Flexural waves from a ground shot S recorded by detectors D at distances d=8.4-11.9 inches from the source. B is a barrier for blocking the horizontally travelling air pulse.

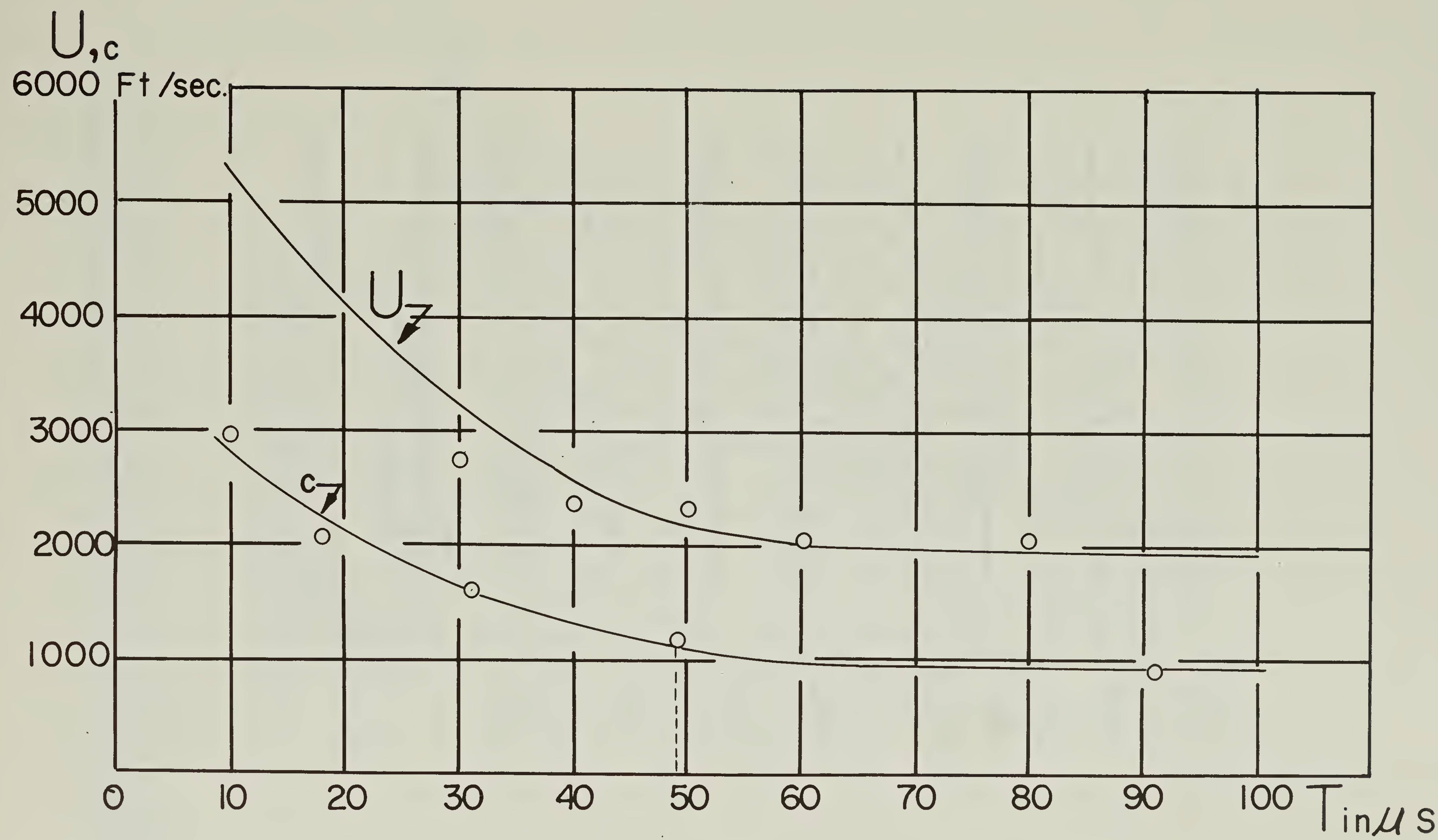

Fig. 2. Comparison of theoretical and experimental values of phase (c) and group (U) velocity for 24 st aluminum, 1/32 inch thick.

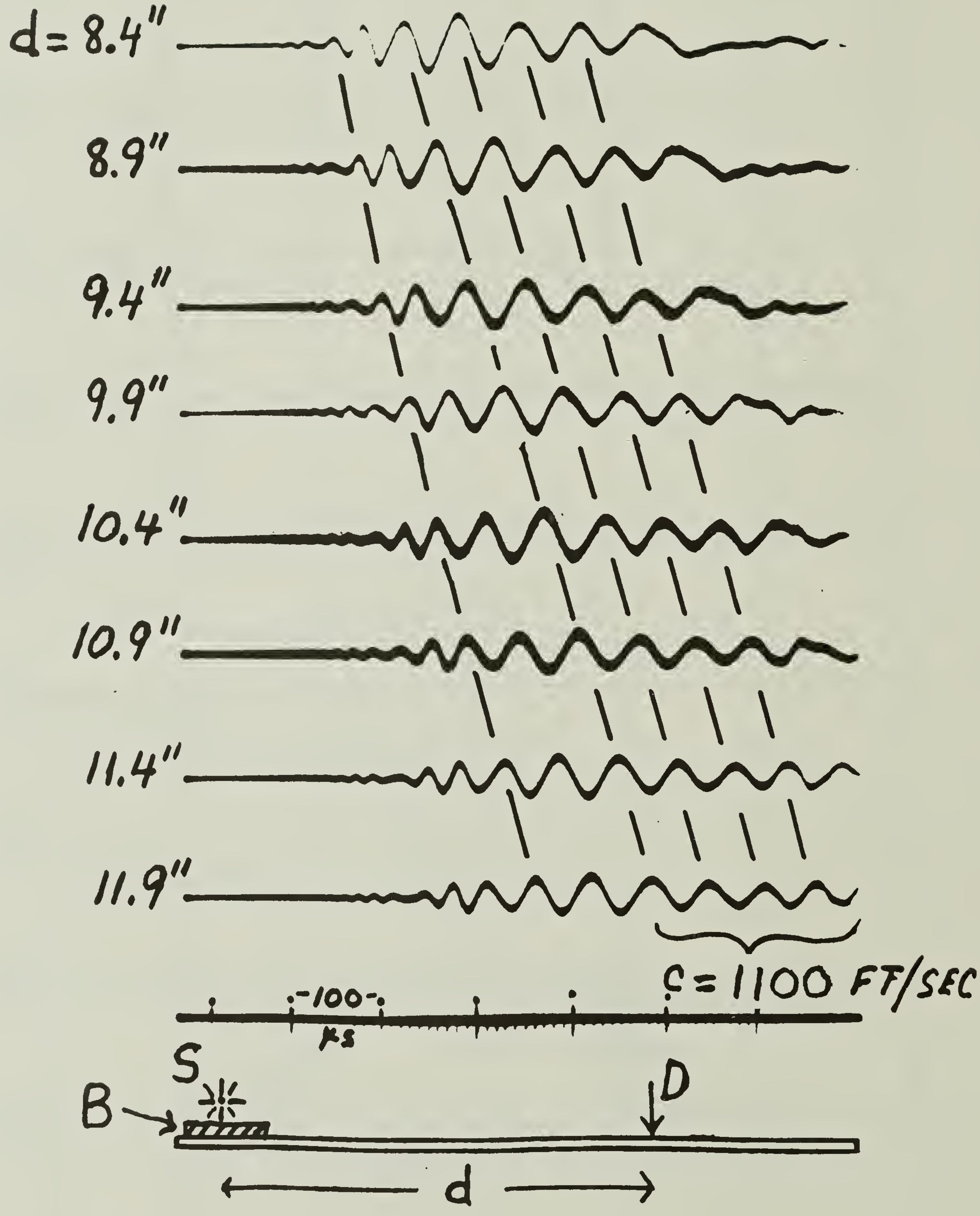

Fig. 3. Flexural waves from an air shot S recorded by detectors D at distances d=8.4-11.9 inches from the source. B is a barrier for blocking the air pulse from the plate in the vicinity of the source.

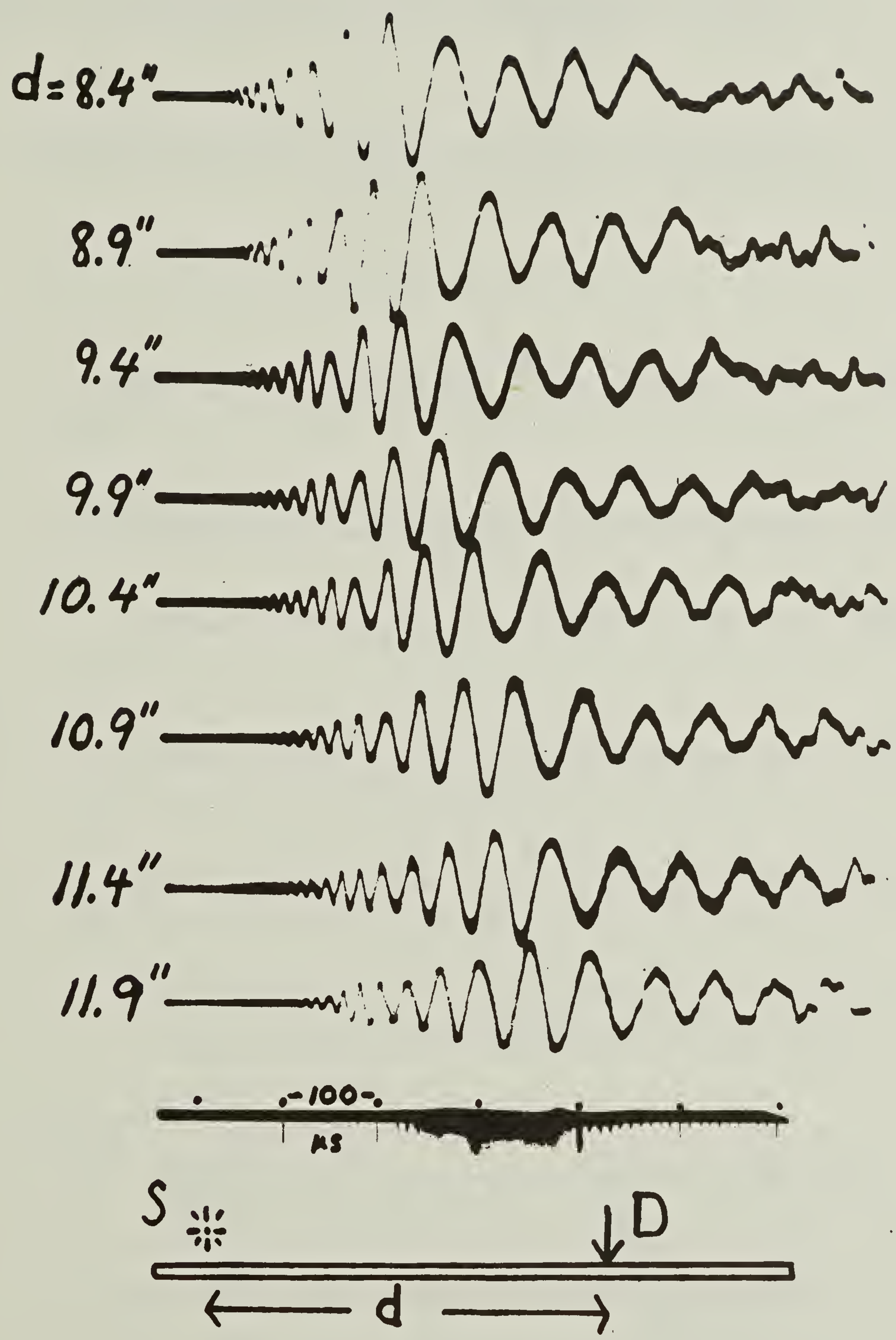

Fig. 4. Flexural waves from a combined air and ground shot S recorded by detectors D at distances d=8. 4-11. 9 inches from the source.

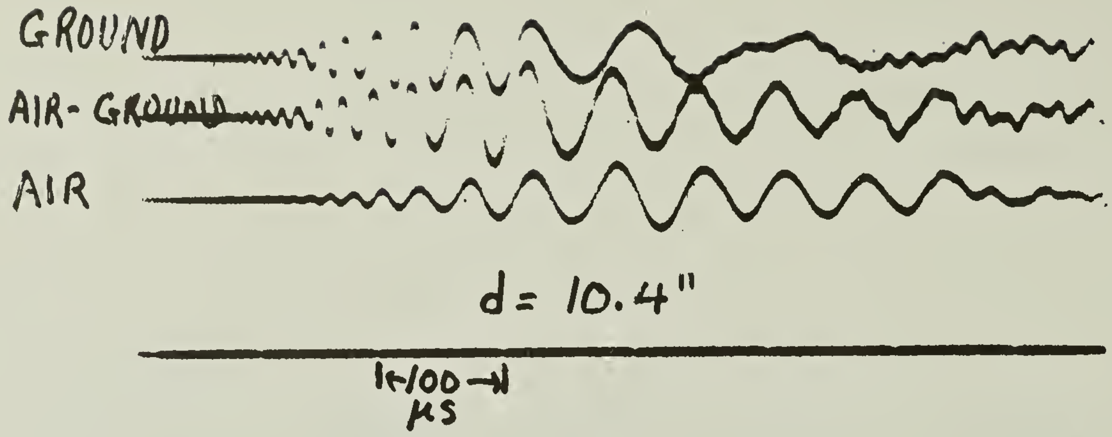

Fig. 5. Flexural waves from a ground, air-ground, and air shot at a distance of 10. 4 inches from the source.

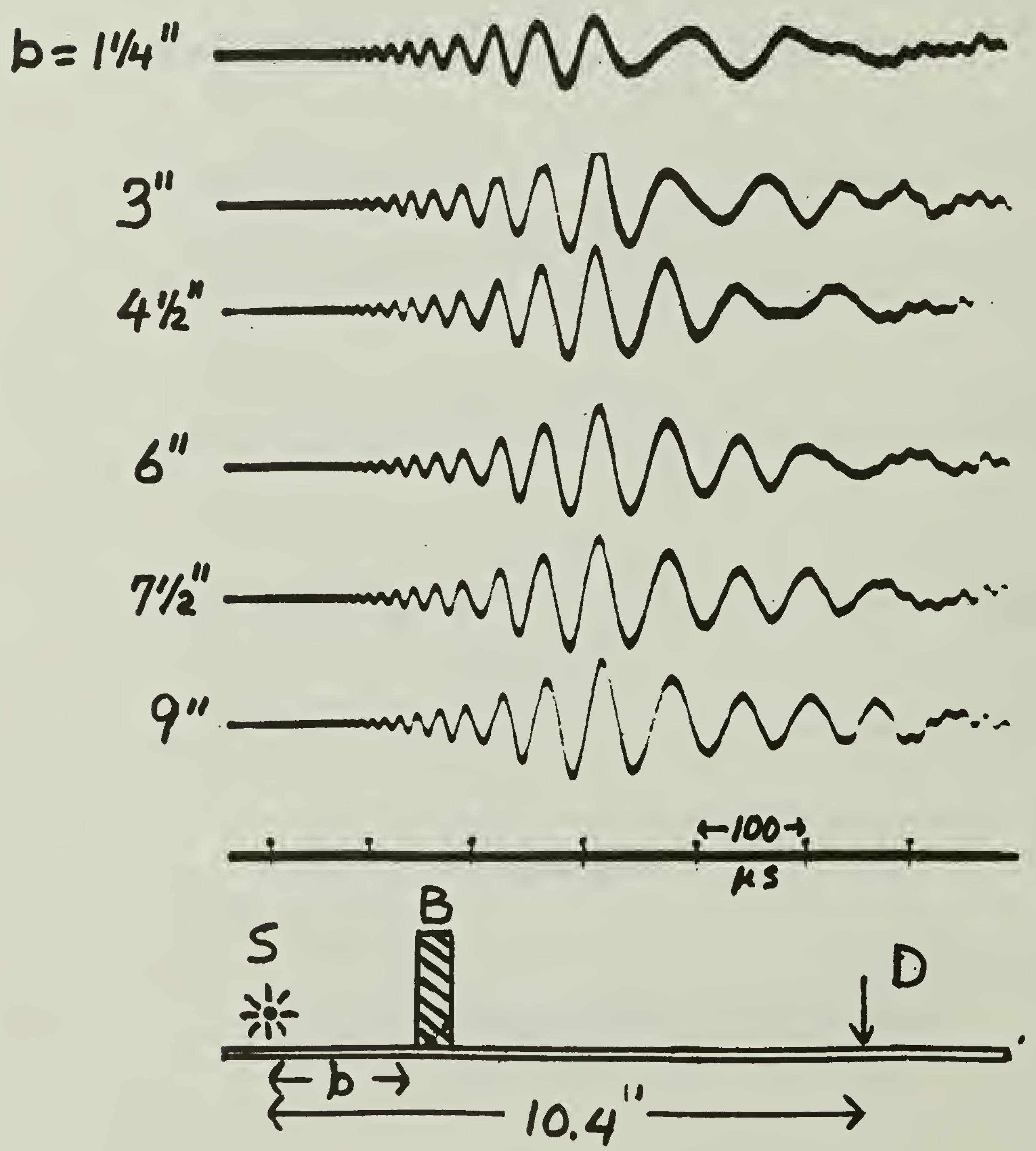

Fig. 6. Flexural waves from a source S for various air-fetch distances b at shot-detector distance of 10. 4 inches.

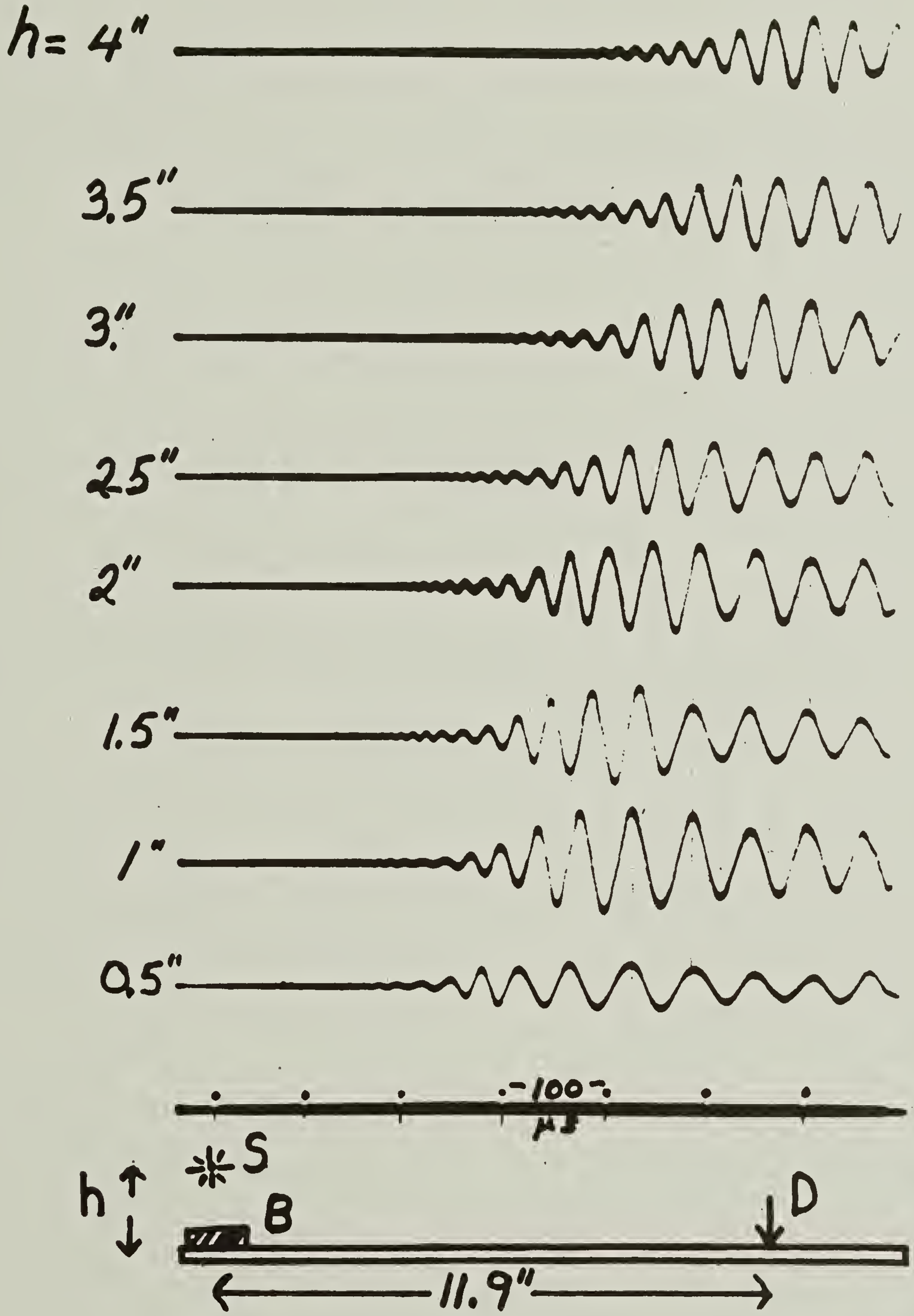

Fig. 7. Flexural waves recorded at shot-detector distance of 11.9 inches for various heights h of an air source S.

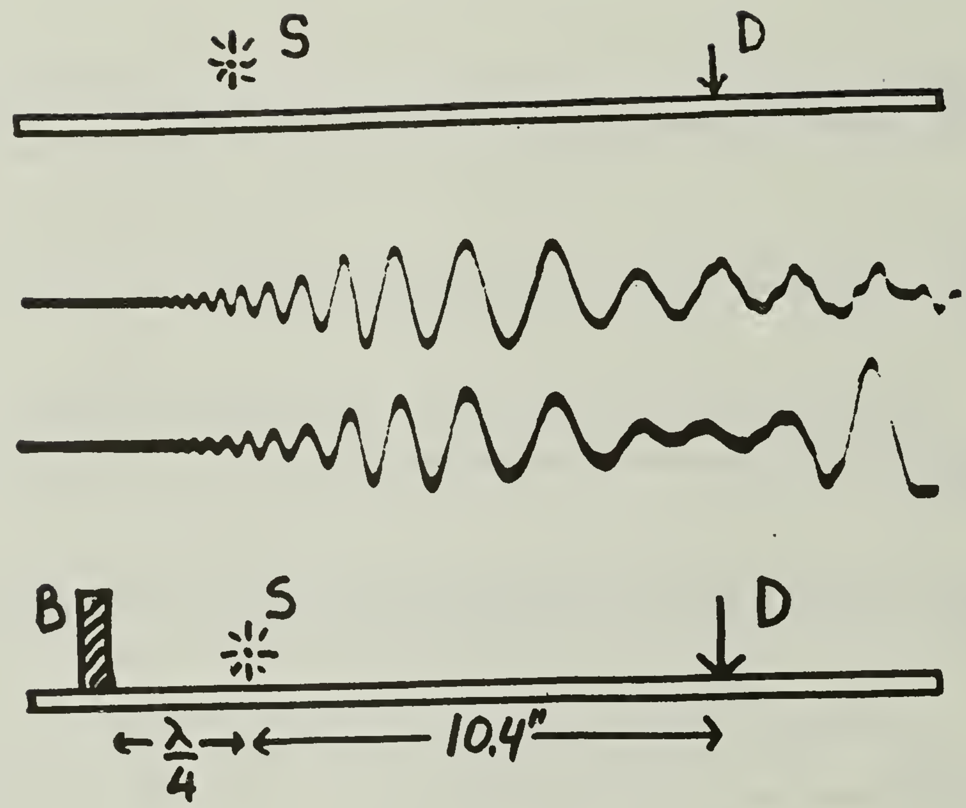

Fig. 8. Flexural waves from air-ground shot S recorded at distance of 10.4 inches. Lower trace shows cancellation of air-coupled waves by destructive interference between direct and reflected air pulse.